LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T1000337-v4 *Advanced LIGO* 16 September 2010

Monolithic Stage Final Design Review Document

A. S. Bell, N. Beveridge, A. Cumming, L. Cunningham, G. Hammond, K. Haughian, R. Jones, R. Kumar, M. Van Veggel, K. Strain, J. Hough, S. Rowan
Institute for Gravitational Research, University of Glasgow

Distribution of this document:
LIGO Scientific Collaboration

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California
Pasadena, CA 91
Phone (626) 395-2
Fax (626) 304-98
E-mail: info@ligo.calt

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
bridge, MA 02139
ne (617) 253-4824
x (617) 253-7014
l: info@ligo.mit.edu

Institute for Gravitational Research
University of Glasgow
Kelvin Building
Glasgow G12 8QQ
Phone: +44 (0)141 330 3340
Fax: +44 (0)141 330 6833
Web: www.physics.gla.ac.uk/igr/

LIGO Hanford Obse
P.O. Box 159
Richland WA 99
Phone 509-372-81
Fax 509-372-8137

ivingston Observatory
P.O. Box 940
ngston, LA 70754
one 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

Final design review document for the monolithic stage of the aLIGO ETM/ITM

Revision History

Revision	Changes	Name	Date
-v1	Initial release	Angus Bell	31st Aug 2010
-v2	Addition of vertical contribution to thermal noise	Angus Bell	1st Sept 2010
-v3	Addition of revision table Addition of FRD check list Correction of a number of small errors	Angus Bell	2nd Sept 2010
-v4	Correction of small errors and updates based on FDR actions	Angus Bell	9th March 2011

1. Introduction

This document provides an overall summary of the monolithic part of the quadruple pendulum suspensions to be used in aLIGO. It will also deal with some auxiliary systems that need to be reviewed and are included here to avoid oversight. To be specific, this means the scope of the review will cover

- The production of fibres for suspending the ETM/ITM
- The welding of the fibres to both the ETM/ITM and the PUM
- The attachment of the break-off prisms to the PUM
- The attachment of the break-off prisms to the ERM
- The attachment of the magnet flags to the PUM

A number of items are mentioned in this review to provide a more complete narrative but they are not being reviewed at this time. These include

- The ETM/ITM and PUM masses
- The ears and their attachment to both masses

The document is laid out in the following way. The science requirements are listed, a short overview of the initial design is given, a list of documents relevant to the review is shown, and then the individual parts of the design are looked at in detail.

2. Science Requirements

1. The horizontal thermal noise should be 10^{-19}m/√ Hz or lower at 10 Hz, per test mass (T010007-v2, page 11).
2. Technical noise sources should be 10^{-20}m/√ Hz or lower at 10 Hz (T010007-v2, page 11).
3. All pendulum modes that couple directly into the sensed direction should lie below 10Hz with exception of the highest vertical mode frequency which can be 12 Hz or lower and the associated roll mode which is expected to be about 1.4 times higher (T010007-v2, page 7 and T020034-01, page 10).
4. The fundamental violin mode frequency should be 400 Hz or higher (T010007-v2, page 7).

3. Overview of design

The conceptual design document is T010103 . A list of the main points impacting the monolithic design is given below.

- A fused silica mirror, forming the lowest stage of the pendulum, will be suspended on four fused silica fibres.
- The fused silica fibres will have a dumbbell design, with a 400 micron diameter cross-section for most of the length and short 800 micron sections at the ends, to simultaneously meet thermal noise and vertical bounce frequency requirements.
- The penultimate mass will also be made of fused silica and (except for the wedge angle) will be identical in size and shape to the mirror.
- The silica fibres will be laser welded to fused silica ears that are silicate bonded to flats on the sides of the penultimate mass and on the sides of the mirror below.

4. Relevant Design Documents and RODAs

T010075	*Advanced LIGO Systems Design*
T010103	*Advanced LIGO Suspension System Conceptual Design*
T000053	*Universal suspensions subsystem design requirements*
T010007	*Cavity Optics Suspension Subsystem Design Requirements Document*
T020034	*Low-frequency Cutoff for Advanced LIGO*
M080363	*ETM/ITM suspensions will use tapered circular cross-section silica fibre*
T080091	*Proposal for baseline change from ribbons to fibres in aLIGO test mass suspension monolithic stage*
M080134	*E/ITM and BS/FM pitch frequencies and d-values*
M080134-v2	*E/ITM and BS/FM pitch frequencies and d-values*
T0900556	*Note on revision of monolithic quad pendulum "d" parameters to enable revised ears and welding*
T1000518	*Quad suspension matlab model parameters*
T050213-v2	*ETM/ITM Monolithic Stage Fabrication and Assembly (cylindrical fibres version)*
T050213-v1	*ETM/ITM Monolithic Stage Fabrication and Assembly (ribbons version)*
T050034-03	*ETM Controls Prototype: "3 &1"Assembly*
T0900447	*Final design document ETM/ITM ears*
T1000239	*CO2 laser fibre pulling machine*
T1000024	*Dimensional characterisation equipment for fused silica suspension fibres*
T080042	*Production of grooves in Noise Prototype break-off prisms*
T0900586	*Vertical bounce frequency tester for ITM/ETM silica suspension fibres*
T0900391	*Pulling/Welding Procedure (LASTI, September 2009)*
E1000027	*Hazard analysis for LASTI test hangs and monolithic hang*
M1000038	*MIT LASTI - CO2 Silica Fiber Pulling and Welding Standard Operating Procedure*
T060039	*Caltech controls method for suspending masses*

E1000006	*Advanced LIGO Quad Suspension Assembly Procedure*
E1000167	*Advanced LIGO Quad Suspension Glass Mass Preparation Procedure*
E1000366	*Pulling/Welding Procedure*
T1000521	*Monolithic Final Design Review Documentation and Drawing Overview*
E1000265	*Jig settings calculation spread sheet*
E1000277	*Preparation of an end or input penultimate mass (ETM-PM/ITM-PM) (Hydroxide-Catalysis Bonding of ears and gluing prisms and magnet flags)*
E1000278	*Preparation of an end or input test mass (ETM/ITM) (Hydroxide-Catalysis Bonding of ears)*

5. Final design for ETM/ITM monolithic suspensions

A full description of the preliminary parameters for the quadruple suspensions is provided in Appendix D of the suspension system conceptual design document (T010103).
An overview of the key design features and the main parameters for the monolithic stage are presented below.

5.1. Monolithic suspension elements

5.1.1. Test mass

The test masses have a diameter of 340 mm and a thickness of 200 mm with flats of height 95 mm and width 200 mm polished on the sides for silicate bonding of the ears, giving a mass of 39.6 kg. A $\lambda/10$ flatness specification for silicate bonding is called out on a 65 x 32.5 mm area within these flats (D080658 and D080657). This allows the ears (60 mm x 21.5 mm bonding surface) to be bonded in position with a significant margin. The material for the ETM is Heraeus Suprasil 312. The material for the ITM is Heraeus Suprasil 311. The ETM/ITM test mass design has been reviewed and approved (April 2009).

5.1.2. Penultimate mass

The penultimate mass dimensions and mass are identical to the test mass. The design drawings are D080128 and D080117 and the design specifications are E080112 and E080090 for the penultimate masses for the ETM and ITM respectively..
The material used for the penultimate masses is HOQ-310. Flats of height 95 mm and width 200 mm are polished on the sides for silicate bonding of ears (D090007) and adhesive bonding of wire break-off prisms (D080479). A $\lambda/10$ flatness specification for silicate bonding is called out on two 65x32.5 mm areas within each of these flats. This allows the ears (bonding surface 60 mm x 21.5 mm) to be bonded in position with a significant margin on one of the areas. The other area serves as a back-up area for bonding in case of required repair as discussed in section 5.5.
The penultimate mass also has four cylindrical recesses in its back surface S2 of diameter 10 mm and depth 2 mm for attachment of the magnet flag assemblies (D070234) for the coil/magnet sensing and actuation at this stage of the suspension. The bases (D1001124) for these assemblies are glued into the recesses.
The PUM designs were reviewed and approved for production in February 2009 (E080172).

5.1.3. Silica ears

The design of the silica ears and the method of bonding them to the PUM and ETM were reviewed earlier in 2010 (T0900447). The fibres are butt-welded to the horns on the ear, using a CO_2 laser. The mass of each ear is 0.022 kg.

5.1.4. Wire break-off prisms for the PUM

The penultimate mass is suspended using two wire loops. The wires run in laser-machined grooves on adhesive bonded, stand-off sapphire prisms, providing low loss break-off points (D080479). The distance between the CoM of the PUM and the effective flexure point of the wire is known as the effective d-distance. In the nomenclature of the quadruple assembly, this is referred to as d_2 *effective*. Due to the finite flexibility of the wire, the effective flexure point is not the same as the break-off point (the position of the sapphire prism) (T080096). For the 620 micron diameter wire used to suspend the PUM, the effective flexure point is 2.9 mm from the break-off point (T0900374). The desired value for d_2 effective is 0.3 mm, requiring that the apex of the prism be fixed at 2.6 mm below the CoM. The wire loops are positioned at +/- 3 mm from the centre of mass along the direction of the beam axis. Further information can be found in the design specification E1000273.

5.1.5. Fibre

The use of cylindrical fibres was approved in RODA M080363, and detail of the reasoning, and of the profile, is given in T080091. The fibres will be produced using the fibre pulling machine and the methods described in T1000239. They are pulled from 3 mm diameter Hereaus Suprasil 2 stock (p/n 09685082). To avoid confusion we shall talk about the fibre assembly, when we mean the dumbbell fibre with lengths of 3 mm stock at either end.

The fibre assembly length and profile were adjusted to meet the constraints from the initial specifications (See "Science Requirements"). Furthermore, there are a number of other considerations due to the practicalities of handling the fibre assembly (T0900556) which result in the final assembly.

The length of the assembly is different from the effective length of the fibre used for modeling purposes, due to the necks and 3 mm stock required for welding. The length of the assembly used in welding is slightly greater than the distance between the horns on the ears on the masses, before the ETM is suspended.

Below is a drawing of a theoretical fibre profile, with important points (attachment point, CoM, flex point) noted. This profile does not include the excess stock (~1 mm at each end) that is consumed in welding. Also shown is the profile of an actual fibre for comparison. The profile of the fibre is stored under D1001024 as an excel file and as a Solidworks model. The positions of the flex points with respect to the CoM of the PUM and E/ITM are given in T1000518-v1.

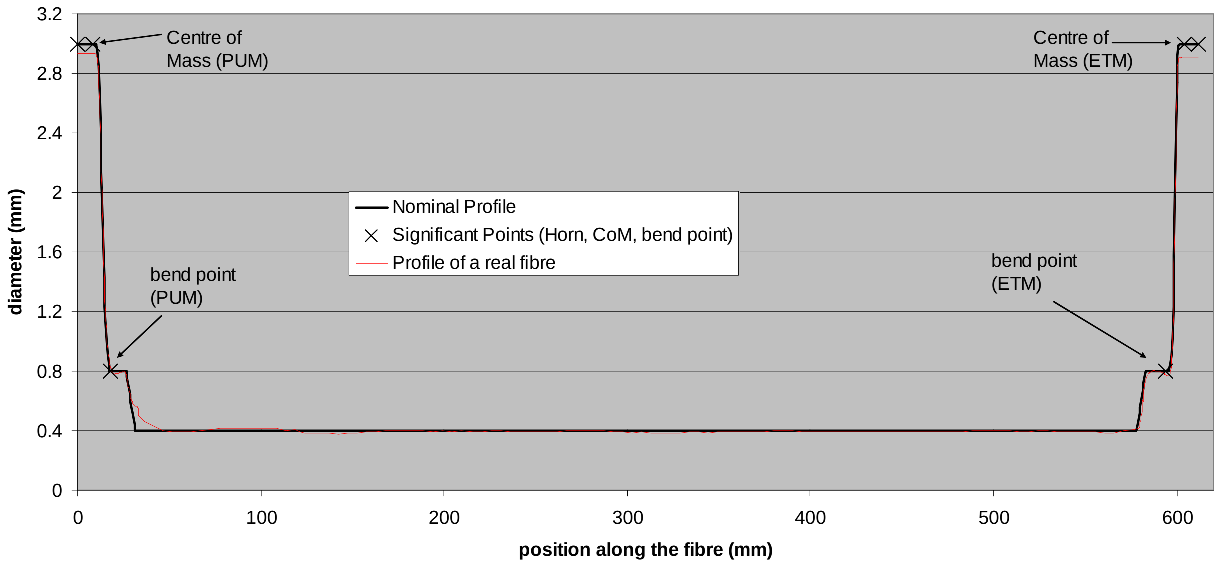

Figure 1. Idealised target profile and actual profile of a fibre assembly

5.1.6. ERM/CP Wire break-off prisms

Although these prisms are not part of the monolithic stage, they are included here as part of the ALUK responsibility. The prisms are documented in D080750. The bonding procedure will be similar to that for the PUM and E/ITM (E1000277) and a modified version will be produced imminently.

5.2. Requirements on interfaces between different suspension elements

5.2.1. Silicate bonding of ears

There are a number of constraints on the final positioning tolerance of the ears. The tightest tolerance comes from the combination of violin mode frequency difference and static pitch. A shift of the suspension point with respect to the CoM by $^1/_8$ th of a millimeter along the beam direction, will produce a 2% change in tension in the fibres, or a 1% difference in violin mode frequency. The change in tension will also lead to a 4 mrad static pitch. The frequencies of the violin modes need to be the same to within about 1% (or 5 Hz) (target value) and the static pitch needs to be set to within a few mrad of the nominal value. Therefore, the ears need to be positioned with an accuracy of ±0.1 mm, with respect to the CoM, to keep the static pitch and violin mode frequencies within tolerance.

In the vertical direction, the ear position relates directly to the flex point position and CoM position, therefore a similar (but slightly lower) tolerance is desirable.

The procedures for bonding the ears onto the test masses and the penultimate mass respectively are detailed in E1000278 and E1000277 respectively. The values that should be used to position the ears using the bonding jigs are in E1000265, which calculates the settings for the jigs based on measurements of the mass. More information can also be found in the report on bonding at LASTI, T1000114.

The ears will be bonded to the sides of the masses using silicate bonding. This is done to minimize thermal noise, as silicate bonds allow for a quasi-monolithic suspension to be created. The thermal noise contribution from the bonds shall be less than 7.10^{-22} m/√Hz at a frequency of 100 Hz as discussed in more detail on page 17 of T0900447 (the final design document for the ears).

5.2.2. Adhesive bonding prisms to the PUM

The sapphire wire break-off prisms shall be fixed to the flats of the PUM using an approved epoxy (the replacement for VacSeal). The required position is symmetrically about the COM in horizontal direction (from surface S1 to S2 of the mass). The vertical position is set by the effective d-distance, d_2, which is 0.3 mm above the COM. Taking into account the flexure length of the wire of 2.9 mm from T0900374, this means the apex of the prism will be at 2.6 mm below the COM. The alignment accuracy shall be ±0.1 mm for both the horizontal and vertical direction. Further details on the prism bonding can be found in the design document E1000273 for the wire break-off prisms and in the mass preparation procedure E1000277. More background can also be found in T1000114.

5.2.3. Adhesive bonding magnet flags to the PUM

The magnet flag assemblies are detailed as per D070234. They consist of an aluminium base, into which a steel ring is glued and an aluminium magnet flag into which steel rings are glued on each end. The base design D070237 has been replaced by a slightly different design D1001124 for the silica masses. Four of these composite bases are glued into the four cylindrical recesses in the penultimate mass using the replacement adhesive for VacSeal. The procedure for this is described in E1000277 and more details can be found in T080245. The magnet flags are attached to the mass by putting a magnet in between the steel ring on the base and the steel ring on one end of the flag. The flag itself can in fact be transferred directly from the metal build penultimate mass to the silica penultimate mass.

5.3. Suspension Preparation

5.3.1. Mass Alignment

The alignment of the PUM and ETM is very important to ensure that the welding process is successful. The PUM is considered fixed in terms of pitch and yaw when it is sitting on the line stops on the catcher structure. The catcher structure and LSAT should be leveled, using a good bubble level (~ $^{1}/_{10}{}^{o}$ or a few mrad). The PUM should be positioned on the supports such that the face that is towards the reaction chain is level with the edge of the catcher structure. The roll of the PUM should be checked by sighting on both ears, or some other appropriate reference, with the total station or the Brunson transit T0900391, and adjusted if necessary. The adjustment can be done by rotating the PUM on the PTFE stops on the catcher structure, without lifting the PUM. The pitch of the PUM can be measured with the total station; it should be nominally vertical, certainly within a few minutes of arc. The ETM needs to be positioned in height and along the axis of the beam, as well as being adjusted for pitch, roll and yaw. The ETM is wedged and normally the thicker part of the wedge is closer to the PUM. The position along the beam is set when the face of the mass is flush with the face of the capture structure. The roll of the ETM can be set in the same way as the PUM. The vertical position is most easily set using a rule cut to the correct size (611.5 mm). If the ends of the rule are cleaned, it can be placed between the horns on the PUM and the ETM to ensure they are separated by the correct distance. The jack is used to lift or lower the mass. The mass should always be lifted initially, then the line stops retracted if the mass it to be lowered. Once the mass is nominally in position the line stops can be brought up under the mass to support it. The pitch can be further adjusted using the line stops and monitoring the alignment with the total station. The pitch of the ETM HR face should be set to equal the pitch of the PUM. The stock is positioned on the horn by eye. It is easy to note if the stock is centred to within 0.15 mm or better

5.3.2. Fibre production

Fibre pulling is discussed in detail in T1000239.

5.3.3. Fibre Characterisation

The fibre profile should be measured for each fibre using the profiler. It has been found that, with reasonable care, fibres can be produced with diameter profiles that match to within 5% for the dumbbell sections and within 2% for the 400 micron section. The 800 micron dumbbell section addresses the cancellation of thermoelastic noise and it needs to be within ±10% of the desired value to ensure tolerable performance. The 400 micron section determines (in the main) both the violin mode frequency and the bounce frequency. The violin mode frequency varies in relation to the integral of the reciprocal of the fibre radius along its length. The variation in this integral, for fibres selected according to the preceding criteria, is around 0.2% (by numerically integrating the data from the fibre profiler). This translates to a variation in violin mode frequency of 1 Hz.
The fibre is profiled to produce a map that gives fibre diameter as a function of distance along its length. This process is fully described in T1000024. The profile for each fibre that is to be used on a suspension should be stored on the DCC as per M1000221.

5.3.4. Weld Tooling

The welding is undertaken with the same laser used for fibre pulling. An articulated arm with gold coated mirrors (Denfotex Light Systems) is used to deliver the laser beam to the suspension structure. A number of "shelves" (D080036) are mounted on the LSAT at appropriate heights to access the ears for welding. The weld head (D080040) is attached to one of the shelves in preparation for welding. The weld head has a Galilean telescope to reduce the beam diameter to a few millimeters at the working point. The articulated arm screws onto the weld head to hold it securely.
A gold coated mirror (D0900950 or D0900951) is positioned behind the horn and the stock to enable the rear of the weld to be accessed. The mirror is held in place by a spring clip that mounts onto the weld hubs (D0900957), which are in turn held in place by the weld scaffold (D080392). The scaffold also holds the fume extraction tube in place. This stainless steel tube is used to extract the silicon dioxide vapour from the weld, caused by vapourisation of the stock and horn by the laser beam. The scaffold mounts on to the LSAT using a pair of clamps.

5.3.5. Welding Process

A description of the weld process is given in T050213-v2 and a stepwise procedure is given in E1000366. The weld is formed when the stock is slowly pushed into the horn at a temperature where the viscosity of the material is low enough to allow them to flow into each other. The laser beam is initially aimed at the front of the horn, just below the top. The area is heated and the beam is moved around to ensure that heat is delivered to the whole horn. It is normally found that having the beam such that part of it heats the front of the horn and part of it passes behind the horn and is then reflected onto the rear by the gold mirror allows maximal heating. When the temperature has increased enough, the stock can slowly be brought towards the horn, with the continuous application of heat by the laser. As the stock moves into the horn you will see a line join between the two parts that will slowly disappear with heating. Around 1 mm of excess stock will be used to create each weld.

5.3.6. De-stress and Pitch alignment

As in the previous section, documents T050213-v2 and E1000366 should be referred to for this procedure. There are a number of different processes that are all dealt with in the so-called de-stress step. These include, tension equalization in the fibres, polishing of the weld and stock to remove any micro-cracks, heating and cooling of the weld area under low tension to help relieve any stress buildup and active setting of the pitch of the ETM. This is done by applying a small tension to the fibres and using the CO_2 beam to heat the weld area to allow the fibres to pull the stock into alignment and relieve any tension on the fibres. This ensures that all fibres will have close to zero tension prior to off-load. De-stress is done in two steps. Firstly the mass is lowered by ¼ turn (0.15-0.2 mm) on the four ¼-20 screws under the line stops on the ETM. All the upper welds then have the CO2 beam applied, until it is obvious that all movement of the stock has ceased. The full weld area, as well as the stock, is polished with the beam at this point. Next, the ETM is lowered again by ¼ of a turn, and the laser autocollimator and total station are used to monitor the pitch. The pitch is adjusted to the desired value and the CO_2 beam is applied to all four lower welds as before. At this point all four fibres should have close to zero tension and the mass should be pitched as required. On off-load, the only factors affecting the pitch will be the difference in fibre cross-sections and the CoM offset with respect to the ear location.

5.3.7. Proof it all works

The technique of welding 4 fibres to suspend a 40 kg mass has been carried out a total of 11 times successfully, the final time for the full monolithic assembly. There were two failures at the start of the experimental trials, which were almost certainly caused by insufficiently controlled methods.

Meeting the requirements:

	Requirement	Reference	Actual value	Reference
Static Pitch	0, +/- 20 mrad	T050212-00	0, +/- 4 mrad	T1000302
Static Yaw	-			
Static Roll	0, +/- 2 mrad	T050212-00	0, +/- 2 mrad	
Mode frequencies				
Pendulum x	0.435, ±0.01 Hz			M080134-v2
Pendulum y	0.463, ±0.01 Hz			
Pitch	>1.2 × Pend x	M080134		
Yaw	0.60, ±0.01 Hz			M080134-v2
Roll	-			
Bounce (z)	< 12 Hz	T010007-v2	8.8 Hz	
Violin modes	> 400 Hz[36]	T010007-v2	515 Hz, +/- 1%	T1000302

Table 1 The frequencies in the table refer to those in the full quadruple suspension, not in the monolithic stage alone

[36] It should be noted that the review committee at the FDR asked that the spread in violin modes be kept with 5Hz. The precision of the fibre production translates this to a specification on the position of the fibres and ears with respect to the CoM position.

5.4. Assembly

Full details of the assembly procedure are given in the fabrication and assembly document for the monolithic stage (T050213-v2) and in E1000366 *Advanced LIGO Monolithic Stage Assembly Procedure*. Here we give a brief overview.

Each suspension is to be built as a wire hang version initially. T060039 describes the methodology for moving from the wire hung metal assembly to the monolithic lower section. The PUM and ETM should be removed and the ears and prisms should be attached as per T0900447.

The monolithic stage is prepared using the lower catcher structure and LSAT. The UIM is installed and the silica PUM should be hung independent of the ETM before the installation of the fibres to check for any issues before moving to the monolithic assembly. The measurements made on the alignment of the PUM at this stage and on the PUM and ETM at the next stage should be recorded for each suspension as outlined in M1000221.

When it is clear that the PUM hangs within required accuracy, the suspension can be passed to the welding stage. The points below give a brief overview of the steps required for the monolithic assembly.

- Prepare masses (bonding ears, gluing prisms and magnet flags)
- Wire hang of PUM and UIM
- Test PUM and PUM + UIM hanging
- Lock down PUM
- Insert ETM
- Move suspension to welding stage
- Align welding stage
- Align ETM
- Weld fibres to ETM and PUM
- Set pitch value
- Suspend ETM
- Install fibre guards
- Move back to triple hang tooling
- Measure ETM alignment when hanging
- Move main chain and reaction chain onto tooling to prepare for joining

5.5. Repair and Recovery Scenarios

The methods used to implement repairs around the silica welds are detailed in T050213-v2 and E1000366. The list of scenarios below indicates the escalation path in potential repairs.

- Weld not good, or stock not centred
  - Continue weld procedure, applying heat to enable movement of the stock
- Fibre touched during welding
  - Remove single fibre using tooling and replace with new fibre
- Fibre touched or broken after all welded, before suspending
  - Fibre should be replaced using the tooling and the de-stress steps will need to be re-applied
- Fibre touched or broken when mass is suspended

- All four fibres must be replaced due to probability that the remaining fibres were touched by flying shards of silica
- The time required for replacement of 4 fibres when the horns have not been damaged will be the same as a new suspension. For the monolithic stage this has been shown to be less than 2 days (*cf*. Glasgow and MIT tests, MIT monolithic hang).

- Horn with minor damaged during fibre break, chips < ½ mm by ½ mm
  - Horn should be polished using the laser beam to seal any micro cracks, new fibre can then be attached as per above.
- Horn too badly damaged to use again (in case of PUM)
  - The ears can be removed by grinding and polishing and new ears bonded on the other side of the CoM line.
- Horn too badly damaged to use again (in case of ETM/ITM)
  - Research is continuing into methods for de-bonding ears that have been cured for longer than a few days. Currently the masses would need to have the ears removed by grinding and the flat sections repolished to allow new ears to be bonded in place.
  - A replacement test mass with new ears should be available to allow the assembly process to proceed in the case of this scenario.

5.6. Thermal noise performance for ETM/ITM quadruple pendulum

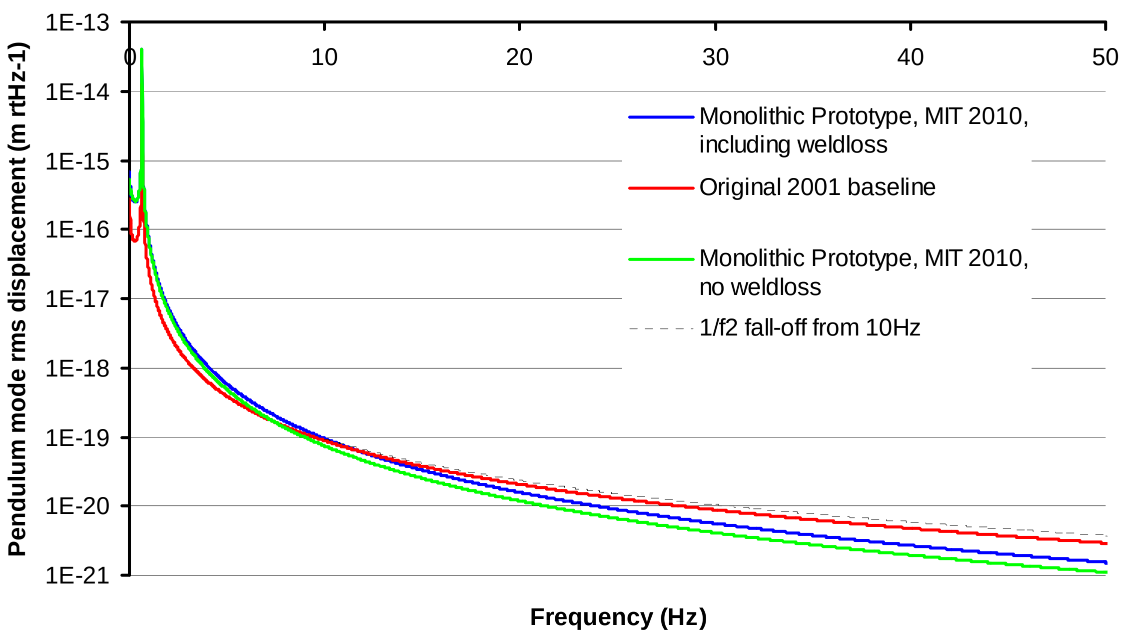

Figure 2. Predicted pendulum mode thermal noise as a function of frequency. See text for detail on the curves.

The method used for thermal noise modeling was described in the suspension system conceptual design document (T010103) and the full methodology and its application to cylindrical dumbbell fibres is detailed in the publication by Cumming et al (*Class. Quantum Grav.* ***26*** *(2009) 215012*, (LIGO-P0900084). The calculation takes account of the losses in the bulk material, the surface

losses and thermoelastic effects. In addition, finite element analysis provides a more accurate method of dealing with the effect of the fibre "neck" on the dilution factor. A further refinement to the calculation of thermal noise in the pendulum mode is the inclusion of the weld loss. The weld loss in CO_2 drawn and welded fused silica fibres has been investigated at some level by Heptonstall et al (*Class. Quantum Grav.* ***27*** *(2010) 035013*, LIGO-P0900095). By comparison of the weld quality on the LASTI suspension with the welds measured in that paper, we estimate a value of $5.8\ 10^{-7}$ for the loss associated with the welded regions. The baseline for the thermal noise at the time of the initial design review did not include weld loss specifically, so for proper comparison we show the thermal noise in the pendulum mode with and without the weld loss term.
To ease the burden of data input for the FEA calculation, the profile of a single fibre was imported into the ANSYS model and copied into all four fibre locations, rather than using four individual profiles. Aside from weld loss, the dominant loss term in the detection band is due to surface loss and the profiles of the real fibres are similar enough for this not to significantly affect the results.
The translation of loss to thermal noise was done for the single stage pendulum modeled in ANSYS. By making direct comparisons between the baseline loss and the actual modeled loss, we show that the system performance will be better than the baseline requirement. Figure 2 shows the calculated pendulum mode thermal noise (rms, m/√Hz) for the original baseline ((T010103-01) (the red curve) and also for the monolithic suspension as created at LASTI. The green curve shows the calculation without the weld loss contribution and the blue curve shows the calculated thermal noise with the weld loss contribution. It can be seen that all three curves have a value of 10^{-19} m/√Hz at 10 Hz as required by the design specification. Above 10 Hz, the curve for the actual suspension drops below the baseline at all frequencies. It should also be noted that the noise drops of faster than f^{-2} (an f^{-2} dependence is indicated by the dotted line in figure 2), as required by the specification.
As well as the thermal noise in the pendulum mode the ANSYS model was also used to calculate the noise in the vertical mode. The standard coupling factor between the vertical mode and the horizontal motion is 10^{-3}. Figure 3 shows three curves: the noise in the pendulum mode, 10^{-3} times the noise in the vertical mode, and the quadrature sum of the two. This calculation is, as before, for the single mass suspension only, so the pendulum mode is at 0.64 Hz and the vertical mode is at 6.5 Hz rather than the 9.2 Hz of the full suspension. The vertical contribution is negligible compared to the pendulum mode noise just over 1 Hz above the vertical mode.

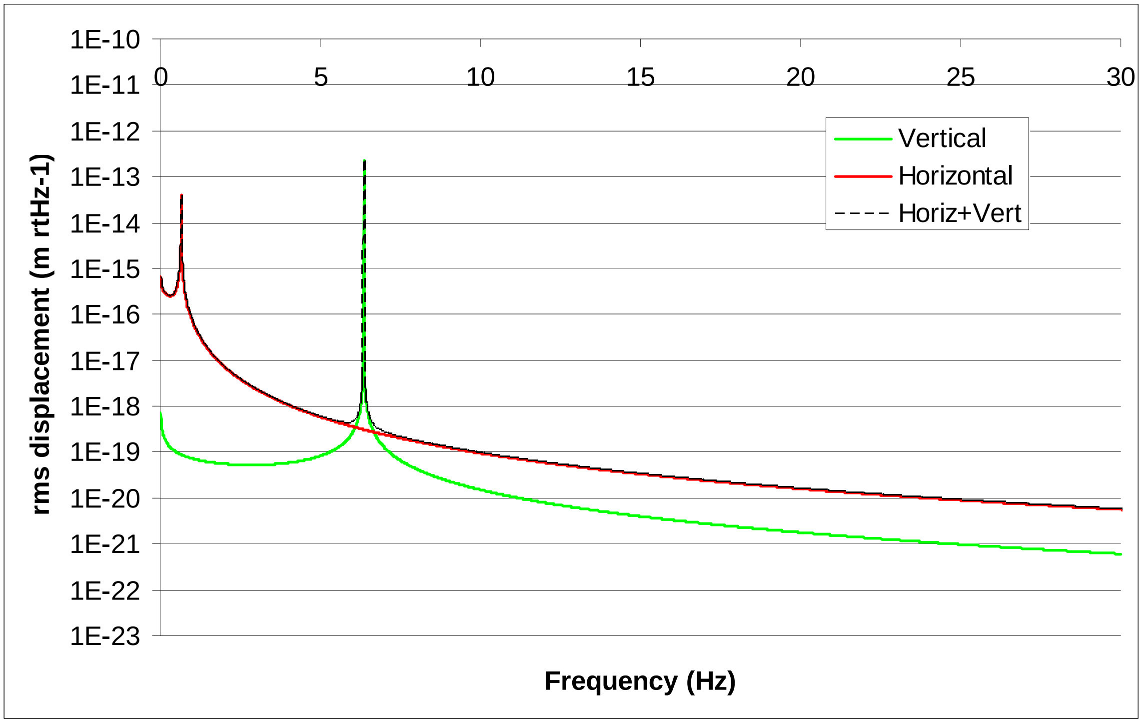

Figure 3 The three curves show the horizontal thermal noise from the pendulum mode, 0.001 of the contribution of the noise from the vertical mode and the quadrature sum of these contributions.

6. *Future support*

6.1. Installation support

The ALUK team will provide support for the first assembly of a monolithic suspension at one of the sites. This is likely to take the form of one or two personnel being on site for 10 to 14 days.
The ALUK team will also provide a full set of the required tooling, most of which is currently at LASTI.

6.2. Training

Training will be provided for personnel at both LLO and LHO. This will consist of 1 week of fibre preparation and handling training followed by 2 weeks of weld training. It is expected that the personnel will be able to spend time with aLIGO equipment practicing after this training event. Some form of refresher training will be required before the first installation and members of the ALUK team will be available to enable this

6.3. Technology transfer

The technology transfer plan is based around having the full documentation available on the DCC to enable the purchase of parts to replicate all of the tooling and equipment used. Instruction manuals for all major items are provided and procedures are available for all of the process involved. ALUK personnel will be available for consultation and support over the period.

6.4. Violin mode sensor for damping

It was anticipated that the very high Q of the monolithic stage may require the use of active damping of the violin modes during science mode to enable a reasonable re-lock time, that is in the absence of an identified ISC method to damp these modes. One method proposed for this would be the monitoring of the movement of the fibers and producing a feedback signal based on that measurement. A prototype version of the VMS has been produced. However, it has become apparent that although the VMS would be useful it is not be necessary and the extra complexity in implementing it would override the advantage of having it. The green interferometer signal can be used to lock the interferometer with the violin modes excited and the violin modes can be “cooled” by feeding back appropriately. A recommendation to this effect was made by Norna Robertson and has been approved (M1000213-v2) by David Shoemaker.

7. *Glossary*

ETM	End Test Mass
ITM	Input Test Mass
CoM	Centre of Mass
PUM	Penultimate Mass
HR	High Reflector (or Reflecting)
AR	Anti- Reflection
RODA	Record of Decision or Agreement
VMS	Violin Mode Sensor
LSAT	Lower Structure Assembly Tooling, used to hold the lower part of the quadruple suspension when it is being assembled

8. *Final Design Review Checklist*

Final requirements – any changes or refinements from PDR?	T010075	*Advanced LIGO Systems Design*
	T010103	*Advanced LIGO Suspension System Conceptual Design*
	T000053	*Universal suspensions subsystem design requirements*
	T010007	*Cavity Optics Suspension Subsystem Design Requirements Document*
	T020034	*Low-frequency Cutoff for Advanced LIGO*
Resolutions of action items from PDR	T050213-v2	*ETM/ITM Monolithic Stage Fabrication and Assembly*
Subsystem block and functional diagrams	T050213-v2	*ETM/ITM Monolithic Stage Fabrication and Assembly*
Drawing package (assembly drawings and majority of remaining drawings)	E1000036	*SUS_Drawing_Tracker*
Final parts lists	T1000521	*Monolithic Final Design Review Documentation and Drawing Overview*
Final specifications		*As requirements*
Final interface control documents	T050034-03	*ETM Controls Prototype: "3 &1"Assembly*
Relevant RODA changes and actions completed	M080363	*ETM/ITM suspensions will use tapered circular cross-section silica fibre*
	M080134	*E/ITM and BS/FM pitch frequencies and d-values*
Signed Hazard Analysis	E1000027	*Hazard analysis for LASTI test hangs and monolithic hang [needs to be updated for sites]*
Final Failure Modes and Effects Analysis		
Risk Registry items discussed		
Design analysis and engineering test data	T1000337	*Monolithic Stage Final Design Review Document*
Software detailed design		*N/A*
Final approach to safety and use issues	M1000038	*MIT LASTI - CO2 Silica Fiber Pulling and Welding Standard Operating Procedure* (to be updated for the sites)
Production plans		
Plans for acquisition of parts, components, materials needed for fabrication		
Installation plans and procedures	T050034-03	*ETM Controls Prototype: "3 &1"Assembly*
	T060039	*Caltech controls method for suspending masses*
	E1000006	*Advanced LIGO Quad Suspension Assembly Procedure*

	E1000167	*Advanced LIGO Quad Suspension Glass Mass Preparation Procedure*
	E1000366	*Pulling/Welding Procedure*
Final hardware test plans		
Final software test plans		*N/A*
Cost compatibility with cost book		
Fabrication, installation and test schedule		
Lessons learned documented, circulated		*To be compiled, circulated and checked against current procedures*
Problems and concerns		*To be compiled and added to this document*